A CONCEPTUAL DESIGN STRATEGY FOR LIQUID-METAL-WALL INERTIAL FUSION REACTORS

M. J. Monsler and W. R. Meier
Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

ABSTRACT

The liquid-metal-wall chamber has emerged as an attractive reactor concept for inertial fusion energy conversion. The principal feature of this concept is a thick, free-flowing blanket of liquid metal used to protect the structure of the reactor. The development and design of liquid-metal-wall chambers over the past decade provides a basis for formulating a conceptual design strategy for such chambers. Both the attractive and unattractive features of a LMW chamber are enumerated, and a design strategy is formulated which accommodates the engineering constraints while minimizing the liquid-metal flow rate.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract no. W-7405-ENG-48.

1. Introduction

As the experimental fusion-physics programs approach demonstrations of the scientific feasibility of igniting high-gain inertial fusion targets, we must look ahead to the technology development required to bridge the gap between an understanding of the physics and the operation of a fusion power plant. Conceptual design studies of future reaction chambers and power plants are a key element in this process. They are our most valuable tool for assessing the technical feasibility and economic and social costs of fusion power.

The Liquid-Metal-Wall (LMW) is a particularly promising concept for a pulsed fusion energy conversion chamber [1-16]. The dominant feature of this concept is the thick, free-flowing blanket of liquid-metal used to protect the structure of the inertial fusion reactor. An example is shown in Fig. 1. Having studied this concept for several years in conjunction with our industrial and university partners, we have tried to distill our understanding of this concept into a design strategy that will allow the fusion engineering community to find the path of minimum development effort.

The most striking and important feature of inertial fusion, in terms of its impact on reactor design, is that the confinement of the fusion plasma is decoupled from the functions of the reaction chamber wall and structure. Because the physics of energy absorption, implosion and ignition of the plasma are physically separable from the chamber conditions and structural requirements, an extraordinary degree of engineering flexibility is gained compared to the stringent demands that magnetically-contained plasmas place on wall materials. To be sure, the propagation of the driver energy (either laser or ion beams) through the chamber to the target depends on the chamber pressure, and the design of the first wall still depends on the nature of the output radiation from the fusion pellet, but these can be readily accommodated.

In inertial fusion, this degree of freedom can be exploited by placing fluids (gases or liquids) inside the reaction chamber to protect the wall from ablative material loss due to the energy deposition of the short-range fusion radiation (25-35% in soft x rays and debris) and, in some cases, radiation damage due to deeply penetrating x rays and neutrons. Of course, nothing is free; new penalties are incurred in placing protective fluids inside the reaction chamber. Combining the use of protective fluids with the pulsed nature of the energy release leads to engineering constraints and techniques that are radically different from magnetic fusion. The understanding of the dynamic response of fluids and structures becomes most important, with far less emphasis placed on the development of tougher new materials or the design of cooled blanket modules with high thermal performance.

The wall lifetime can be extended by using either gases or liquids in the fusion chamber. Gases are attractive because they can be pumped in and out of the chamber quickly enough to achieve a high rep-rate (> 5 Hz) with relatively little pumping power. However, gases are only effective in protecting the walls against the minor fraction of fusion radiation in x rays and debris; the neutrons penetrate to the wall unaffected. On the other hand, liquids absorb not only the x rays and debris, but also the major energy-carrying component, the neutrons. Of the liquid metals, lithium, lead, and lead-lithium alloys are the most attractive. Because practically all the fusion energy ends up in the liquid metal, separate heat transfer systems for the chamber gas and blanket coolant are not required.

Liquid-Metal-Wall chambers can span the chamber pressure range of 10^{-5} to 10^{-1} torr leading to an environment suitable for the propagation of either laser or heavy ion beams. The LMW flow pattern can be arranged to cover almost the entire wall area of the chamber, leaving apertures just large enough to allow entry of the pellet and driver beams.

The LMW design can be made quite insensitive to the energy partition and energy spectra of x rays, ions, and neutrons. This is an attractive feature, for at this early stage of inertial fusion the characteristics of a reactor-size pellet are not well specified.

The greatest advantage of LMW chambers accrues from the fact that 95% of the neutron energy can be absorbed before the neutrons encounter the solid structure. This leads to an advantage of over an order of magnitude in both increased wall lifetime and reduced mass of activated steel, compared to either a gas-filled inertial fusion reactor or a magnetic fusion reactor. We shall now explore these attractive features of LMW chambers in more detail and discuss the difficulties which arise in their design. We also summarize what has been learned in a set of guidelines for LMW reactor design. A review of some conceptual designs is given in Ref. 1.

2. Positive and Negative Features

A firm foundation for a design strategy can be built by enumerating both the attractive and unattractive features of LMW chambers, and then searching for a conceptual design approach and physical configuration that enhance the positive aspects and minimize the negative aspects. First the positive features:

- Wall-Protection. The structure is protected from short-range fusion products by a layer of liquid metal sufficiently thick to absorb all the debris and all but the hardest x rays, over more than 98% of the solid angle. This eliminates the need for a sacrificial wall, which in general requires fastening a hot brittle material to a cold supporting structure.
- Self-Renewing. The liquid wall is continuously self-renewing. If required, it can be replaced entirely in the time between pulses. Remote replacement of activated solid walls is avoided.
- Neutron Absorption. The neutrons are attenuated and moderated in the liquid metal before they reach solid surfaces. Less than 5% of the neutron energy need reach the structure, with a highly degraded spectrum. Neutron damage rates are significantly reduced [17-23].
- Direct Energy Deposition. The energy from all three types of fusion products (photons, ions, and neutrons) is deposited directly into the heat transfer medium, without having to first pass through a solid surface. The heat transfer liquid is a metal with high heat capacity and heat conduction coefficient [24].
- Tritium Breeding. Using either lithium or lead-lithium mixtures, sufficient tritium is bred in the LMW to obviate the need for supplemental blanket modules [18,25].
- Low Activation of LMW. Lithium's main activation product is the tritium needed in the reactor fuel cycle.
- Beam Propagation. The low vapor pressure of liquid metals at temperatures interesting for energy conversion (400-500°C), coupled with the ability to direct liquid flow to avoid the path of propagating beams, allows the use of either lasers or heavy ion beams in a mode approximating propagation in a vacuum [26,27].

- Self Pumping. The majority of gas in the chamber arises from the ablation due to absorption of x rays and debris. This vapor is self-pumped by condensation to the very large surface area of relatively cold liquid in the chamber. Although vacuum pumps are required for the noncondensible, nonabsorbed gases (primarily helium), the volume flow is small, recovery of heat is not required, and the pumping power is negligible [28-30].

These positive features of LMW chambers lead to substantial advantages for a power-producing technology. The lack of wall ablation and the large attenuation and moderation of neutrons allows the design of a structure which should not require replacement for the entire 30-year life of the power plant. The moderate operating temperature (500°C) and low neutron dose allow the use of common low alloy steels, leading to two extremely important implications: no new exotic material need be developed, and the cost of the required materials qualification program is minimized. The combination of long structural life and a low-chromium, nickel-free steel leads to a very low total mass of activated structure, perhaps over a factor of 20 less than a 316-SS Tokamak [31]. Because $\sim$ 95% of all the fusion energy released is absorbed in the free-flowing liquid metal, separate heat transfer systems for gas cooling, wall cooling, and blanket cooling are unnecessary. The liquid metal heat transfer loops operate at low pressure. Simple, high-power density chamber configurations are possible which do not require complex blanket modules having large temperature and pressure gradients, close tolerances or kilometers of weldments. Finally, because the LMW chambers will allow either laser or heavy ion drivers, there is an advantage in reduced development risk.

Of course, LMW chambers have negative aspects which must be minimized either by clever design or early attention to experimental development. Most of them are specific to liquid-metal systems. The negative aspects are:

- Flow Rates. Large flow rates of liquid metal are costly in the capital cost of pumps and piping, in the capital cost of additional containment volume and, in the case of lead, in the recirculated electricity required for pumping. New pump development programs for metals other than sodium are required [32].
- LM Hazards. A large inventory of liquid metal ($\sim 10^3$ tons) is required. Although the amounts are comparable to the requirements of an LMFBR the size of SUPERPHENIX, the safety issues are different. The potential fire hazard and toxicity of lithium in the extreme event of breach of containment is an issue. The dispersal by a lithium fire of tritium and of radioactive target elements dissolved in the liquid metal, are of concern in postulating the maximum credible accident.
- Pulsed Stresses. The presence of any fluid in an inertial fusion chamber provides a mechanism for creating fluid momentum, leading to an impact stress in the chamber wall [33-39].
- Rep-Rate. The repetition rate of LMW chambers is limited by the time it takes to inject a new LMW into the chamber. Smaller chambers do not help a great deal because the thickness of liquid metal required to stop a neutron, and the practical upper limit on velocity, are relatively fixed. The rate of condensation of vaporized liquid may also set a limit, but it now appears that the flow conditions are more restrictive.
- Chemistry. All the elements from fusion targets will end up in the liquid metal,

along with corrosion products, and many will become activated. Because it is a detriment to have activated material circulating through the primary heat transfer loop, methods of extracting these materials must be devised. Tritium extraction appears to be one of the easiest [40-41]. Also, although pure liquid metals are relatively benign in contact with candidate steels, the corrosion rate is considerably enhanced by the presence of impurities, e.g., nitrogen in lithium. Clearly, the chemistry must be controlled [42-45].

- o Secondary Loop. A secondary heat transfer loop appears to be required to isolate the primary liquid metal loop from the steam feed water loop. Although accident safety is our first concern, the inclusion of a sodium intermediate loop also allows cold trapping of diffused hydrogen isotopes to very low levels during normal operation.
- o Irradiation Geometry. LMW chambers are most attractive if replaceable beam tubes are not needed, i.e., if the liquid wall can be parted in a few places to admit the driver beams and pellet. The concept is most attractive if the irradiation is from 2 to 6 sides and accounts for small total solid angle, although each aperture may admit a cluster of high f/number beams.

These limitations of the LMW concept add to the basis for formulating a design strategy, since they either form the constraining boundaries of design space, or form a penalty function representing costs or factors to be minimized.

3. Guidelines for Design of a LMW Chamber

The engineering constraints and tradeoffs discussed in Ref. 1 provide a strong motivation to devise a design methodology which will organize the many factors involved. We therefore present a summary of what we have learned over the last few years in the form of a suggested design strategy.

There is great risk of oversimplification in attempting to give a set of rigid design guidelines because engineering tradeoffs are inevitably more complex than stated. Many exceptions to the guidelines can be found, yet the alternative of stating all the important factors "to be globally optimized" is uninstructive. With this proviso, the following guidelines are offered as a basic strategic framework for pulsed fusion chamber design using a damage-proof, reestablishable LMW.

1. Select a yield and rep-rate based on the desired electric power output and reasonable assumptions for pellet gain, driver characteristics, and estimated recirculated power requirements. (The resulting design will almost certainly suggest a more attractive combination of yield and rep-rate, leading to an iterative design procedure.)

2. Select a liquid metal based on the tradeoff between pumping power requirements and potential safety considerations. Lead requires approximately ten times more recirculated pumping power than lithium, but a lithium system must be designed to minimize the potential hazard of the stored chemical energy of hundreds of tons of lithium.

3. Select a thickness of liquid metal and chamber wall radius to achieve a structural lifetime equal to the power plant lifetime, based on radiation damage constraints. This will minimize the total mass of activated structural material.

4. Provide high enough flow velocity to insure re-establishment of the LMW, and provide sufficient fluid area to recondense the vaporized liquid within the desired interpulse time.

5. Choose a low alloy, low activation, low corrosion, low radiation damage ferritic

steel to minimize the required materials characterization and development effort.

6. Use a double-shell chamber configuration to separate the radiation and stress loading of the chamber wall from the steady compressive loading of the vacuum and containment vessel.

7. Choose the highest operating temperature and corresponding vapor pressure allowed by driver propagation constraints, and by the strength and corrosion rate of the steel chosen, to maximize electrical conversion efficiency.

8. Since the imposition of a liquid in the chamber provides a mechanism for creating momentum which can be transferred to the structure, seek a LMW configuration which will minimize the induced momentum while absorbing the fusion energy. A two-phase flow will reduce both the kinetic energy imparted to the fluid and the chamber wall stress resulting from the impact.

9. The thickness of the chamber wall and the inner radius of the LMW are chosen simultaneously to meet two criteria on allowed stresses. Increasing the chamber wall thickness will reduce the impact stress, but also increase the peak wall temperature and thermal stress (and decrease the wall strength). Moving the LMW farther from the pellet and closer to the chamber wall will reduce the impact stress without affecting the wall strength or thermal stress, but at a cost of increased flow-rate. Therefore, select the wall thickness which results in positioning the LMW closest to the pellet while meeting both constraints on allowable stress. This strategy minimizes the required mass flow rate of liquid metal.

10. In designing the balance of plant, use an inert atmosphere and many separate steel-lined concrete cells to minimize the hazards of accidental LM leakage. Use an intermediate heat exchanger loop to insure the physical separation of radioisotopes in the LMW loop from the steam loop.

The emphasis in this design strategy is placed on features which minimize social and economic costs while meeting the engineering constraints. Minimizing the mass of activated material and minimizing the power recirculated for pumping are primary examples. The majority of problems in inertial fusion reactor design (e.g., radiation damage, impact stress, thermal stress) can be solved by increasing the liquid metal flow rate and inventory, but liquid metal pumping and plumbing are costly in both component cost and required containment volume. Therefore, innovations in the design of the chamber and loop configurations directed toward minimizing the LM flow rate and thus the pumping cost, LM inventory, building space and recirculated power have extremely high leverage.

We hope that this simple strategy will form the basis of a broad industrial effort to design and engineer more sophisticated LMW reactors, which will lead in turn to a technically feasible inertial power plant constructed of readily available materials, at acceptable economic and social cost.

4. Acknowledgment

The authors would like to acknowledge the support, ideas, criticism, and good humor of their current and former colleagues at Livermore; J. Blink, L. Glenn, J. Hovingh, J. Maniscalco, J. Pitts, and P. Walker; the valuable assistance of their industrial and university partners at Bechtel National, Colorado School of Mines, the Energy Technology Engineering Center, Grumman Aerospace, Rockwell International, and the University of California at Davis; and the highly professional secretarial support of A. DeRodeff.

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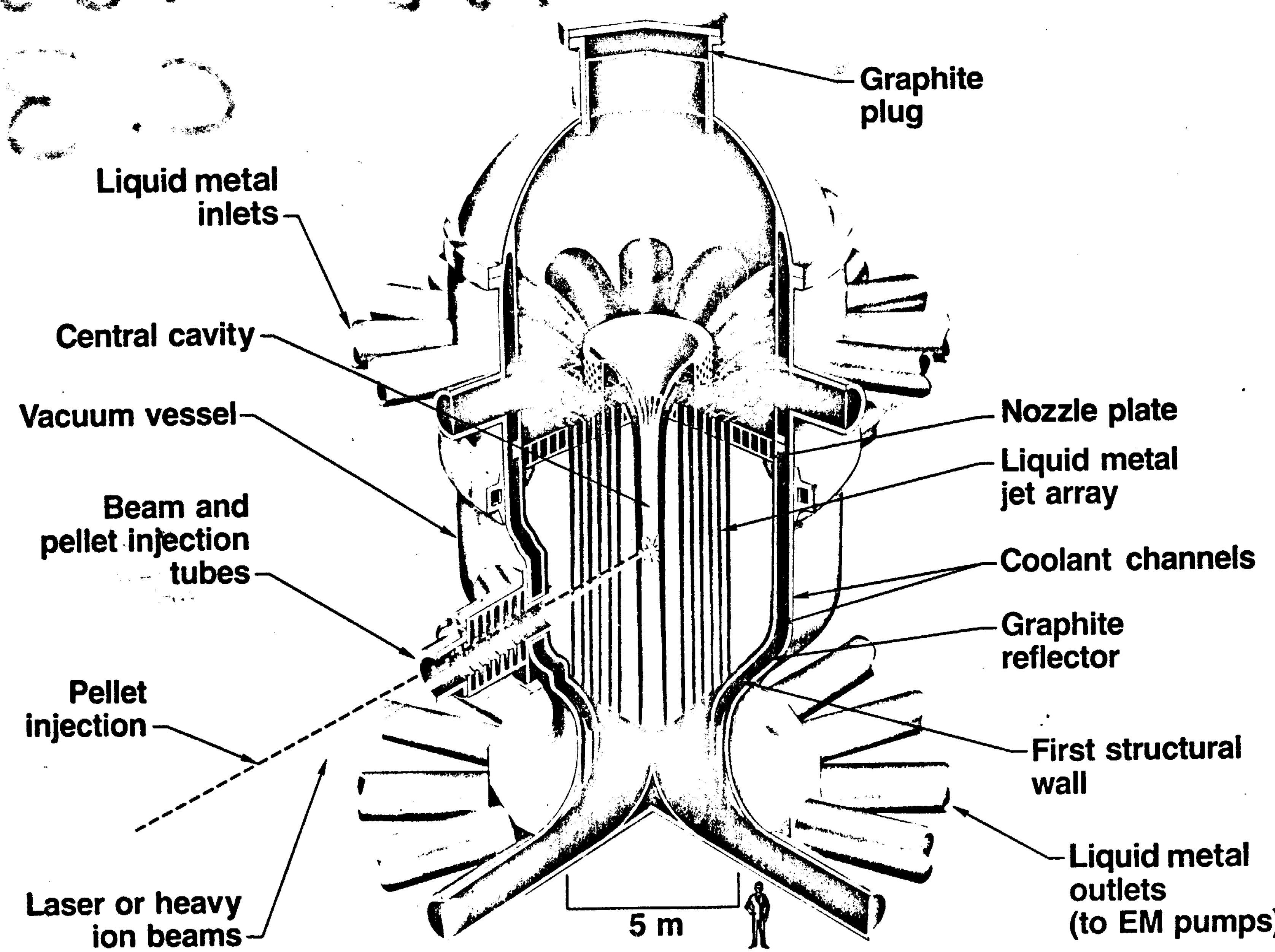
Figure Caption

1. HYLIFE Reaction Chamber.

HYLIFE REACTION CHAMBER



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